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Gold, farms, and forests: Enforcement and alternative livelihoods are unlikely to disincentivize informal gold mining

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Abstract

Informal gold mining (IGM) is a major driver of deforestation and source of global mercury emissions. Policy makers may seek to control the spread of IGM by enforcing rules and/or providing alternative livelihoods. We investigated the dynamics and drivers of IGM in northern Myanmar to shed light on the conditions needed for alternative livelihood and enforcement interventions to succeed. We surveyed 226 respondents who practiced mining and/or farming. We found that mining and agriculture provided complementary livelihoods for many respondents as they met different livelihood needs, and that many of the miners were economic migrants. Livelihood-based interventions based on agriculture/plantations—as currently planned by the regional government—are thus unlikely to provide true substitutes. The willingness of migrant miners to move under different economic circumstances suggests that livelihood-based interventions are unlikely to scale well—mining may simply be displaced to other regions, or new migrants might replace old migrants. We estimated that current enforcement efforts were insufficient and that a much higher level of enforcement—either constant presence of enforcement officials at each informal mining site, or confiscating equipment every month—would be required to make informal mining unprofitable. Enforcement effectiveness was further undermined by corruption in the guise of informal payments to local authorities. Our study is the first to estimate costs that enforcement imposes and the level of enforcement required to deter informal gold mining, and adds to the growing body of evidence that enforcement and alternative livelihood approaches alone are unlikely to deter informal gold mining.

Graham W. Prescott and Aye Chan Maung contributed equally to this work.

KEYWORDS

artisanal and small-scale mining, Burma, conservation, enforcement, gold mining, informal gold mining, livelihood-based approaches, Myanmar

1 | INTRODUCTION

Gold mining has driven deforestation (Alvarez-Berríos & Aide, 2015), soil erosion (Mol & Ouboter, 2003), and mercury pollution (Kumar, Divoll, Ganguli, Trama, & Lamborg, 2018). It has also increased hunting due to migration to mining sites (Owusu, Ofori, & Attuquayefio, 2018). An estimated 16 million people practiced artisanal and small-scale mining in 2011 (Seccatore, Veiga, Origliasso, Marin, & De Tomi, 2014), and many of these operated informally, that is, outside legal frameworks (Sousa et al., 2011). The Minamata convention on Mercury requires its signatories to develop action plans to regulate the (largely informal) artisanal and small-scale gold mining sector, the largest source of global anthropogenic mercury emissions. Policy makers may seek to control the informal gold mining sector by enforcing rules and/or by providing alternative livelihoods (Hilson, 2017; Hilson & Banchirigah, 2009; Siegel & Veiga, 2010). Given the economic and environmental importance of gold mining, and moves to regulate the sector, we urgently need to understand the conditions under which these interventions might work.

Livelihood-based approaches—also known as alternative livelihood (AL) projects—assume that providing alternative livelihood options will reduce natural resource exploitation (Brown, 2003). A systematic review of 106 AL projects found that only 22 met criteria for assessment, and only nine of these reported positive outcomes (Roe et al., 2015). Wright et al. (2016) argued that for AL interventions to succeed they need to provide a multifaceted substitute (e.g., in terms of labor inputs, cultural value, and economic rewards), to target the right users, and to scale to the wider region. AL interventions for informal gold mining (IGM) have often failed because they do not fully substitute mining livelihoods, as in Sierra Leone (Cartier & Bürge, 2011), or because the proposed alternatives are economically uncompetitive with mining, as in Ghana (Hilson & Banchirigah, 2009). In light of efforts to reform IGM to meet the goals of the Minamata convention (Hilson, Zolnikov, Ortiz, & Kumah, 2018) we need tools to systematically assess the potential for AL interventions to work before embarking upon them.

Compliance with environmental regulations can be promoted through social norms, taboos, and the legitimacy of rule-makers (Colding & Folke, 2001). In the absence of effective social sanctions, fines and imprisonment may be used to deter environmentally destructive actions (Keane, Jones, Edwards-Jones, & Milner-Gulland, 2008). Deterrence generally increases in proportion to the penalty but not indefinitely (Arias 2015). The level of enforcement required to make rule-breaking unprofitable can be quantified (Clarke & Cornish, 1985). For example, estimates of the profitability of illegal poaching in Zambia suggested that fines proportional to the number of trophies caught would be the most effective deterrent (Milner-Gulland & Leader-Williams, 1992). Enforcement may also be undermined by corruption (Robbins, 2000). Enforcement approaches should be informed by the profitability of rule breaking and evidence for corruption. As enforcement and AL are common approaches to reforming IGM (Hilson, 2017; Hilson & Banchirigah, 2009), it is critical to assess the potential for enforcement to deter IGM.

Myanmar contains some of the last large intact forests in Southeast Asia (Bhagwat et al., 2017) (Figure 1). Mining was a major past and is a likely future driver of deforestation (LaJeunesse Connette et al., 2016; Lim, Prescott, Alban, Ziegler, & Webb, 2017; Prescott et al., 2017), particularly in northern Myanmar (Papworth et al., 2017), which includes globally important intact wilderness areas and threatened biodiversity, for example, clouded leopard and tiger (Naing, Ross, Burnham, Htun, & Macdonald, 2017). The importance of mining to Myanmar's economy is expected to increase following the opening of Myanmar's economy to global investment after political reforms beginning in 2011 (Webb, Phelps, Friess, Rao, & Ziegler, 2012). Regulating the expansion of informal mining in northern Myanmar is therefore a local policy and global biodiversity priority.

Permitting, alternative livelihoods and enforcement constitute the three pillars of regulating IGM in Myanmar. Under Myanmar Mining Law, gold mining permits are allocated in specific sites for fixed periods of time by the National Mining Enterprise No. 2 (ME2), pending approval of other line ministries at the national and regional level (e.g., General Administration Department [GAD] and Forest Department). At the time of this study, the smallest available parcels of land allocated for legal mining were 20 acres (~8 ha). Informal gold mining, which we define as all mining that occurs without official permits, is considered illegal.

The regional government of Sagaing (located in Northern Myanmar) has made curbing informal gold

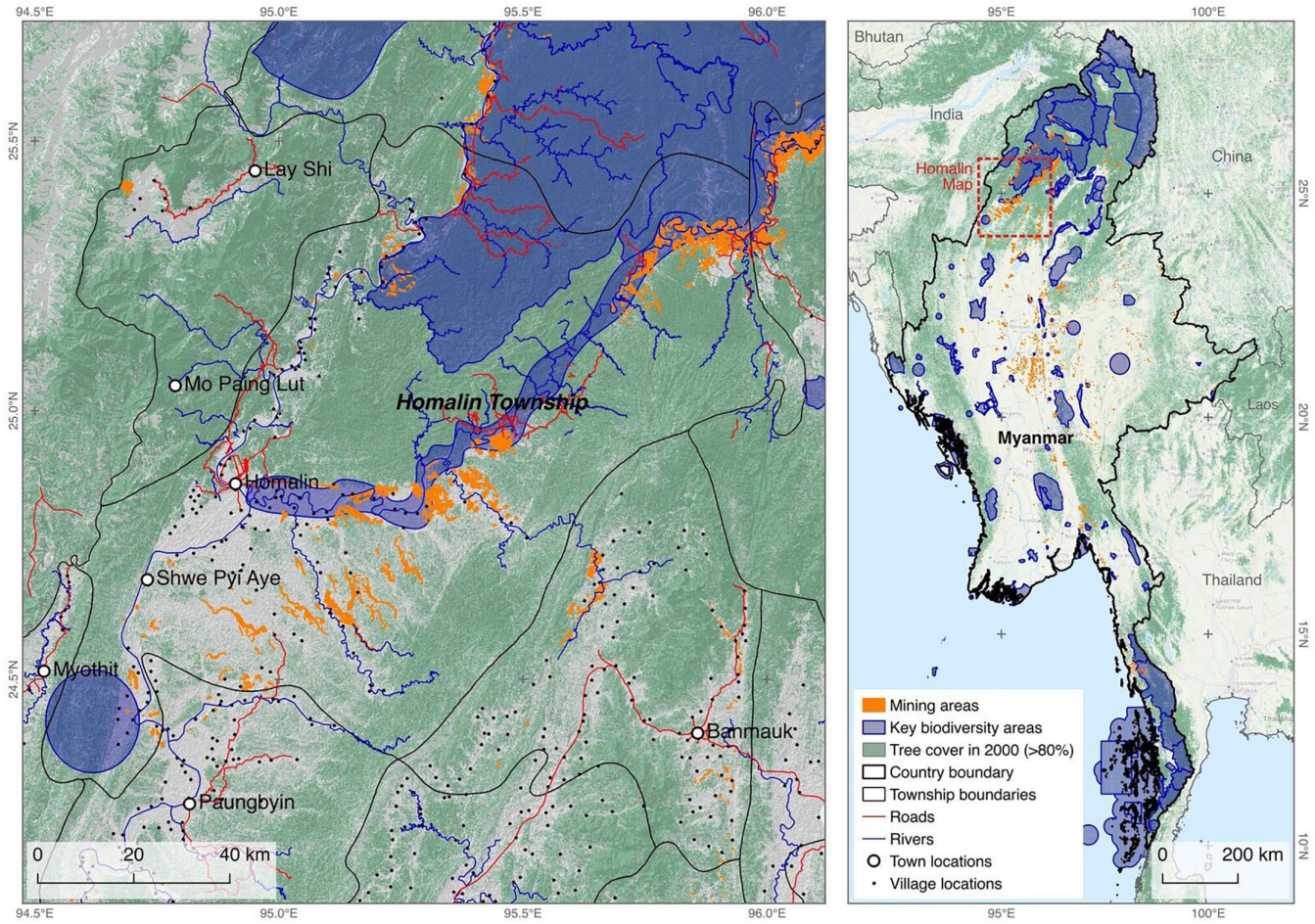

FIGURE 1 Mining sites, forest cover, and Key Biodiversity Areas within (a) Homalin Township, northwest Myanmar (exact sampling points not disclosed to protect participants); (b) northern Myanmar. See Appendix S1 for data sources

mining a policy priority, as expressed by the Chief Minister of the Sagaing to the authors (personal communication June 2017). To do so, alternative livelihoods (agriculture or plantations) and law enforcement are recognized as key measures intended to reduce the prevalence of informal gold mining in Sagaing and Myanmar more broadly. The Myanmar national government has a policy since 2016 of allocating parcels of land (~1.2 ha) to landless citizens, which is to be implemented by regional offices of the GAD based on availability of "vacant" land. Livelihood interventions in the Myanmar context are therefore rooted in the expansion of agriculture. Enforcement of the prohibition on informal mining takes place in the form of periodic raids of informal mining sites by authorities, which can include the military or a team of enforcement officials comprised of representatives from township branches of ME2, Police, GAD, and Forest Department. These enforcement visits may result in the destruction of mining equipment but rarely lead to arrest and imprisonment.

The IGM sector in Myanmar is a growing environmental problem, and requires focused study on the dynamics and potential interventions to mitigate the threat. While the formal mining sector may also have similar, or greater, negative environmental impacts, it can in theory be directly regulated by controls on the number of permits and operating conditions permitted. The informal sector is by definition out of direct regulatory control and therefore other policy measures are needed to manage its spread. Within this context, the aims of this study were to characterize the dynamics and economics of agriculture and gold mining, and of respondents' attitudes toward them, to assess the likely success of proposed livelihood- and enforcement-based policy interventions, and to suggest the circumstances under which they could succeed.

2 | METHODS

2.1 | Study site

Homalin Township (Sagaing Region; Figure 1) has extensive formal and informal mining sectors, which threaten

areas of conservation significance. Controlling the spread of informal gold mining is therefore an environmental policy priority in the Region (Appendix S1). Following initial field visits in May 2017, we selected gold mining sites along the Chindwin River and the Uru River basins that were representative of informal gold mining in Myanmar (Appendix S1), noting that we were not able to access some gold mining areas in the township for physical accessibility or security reasons.

In Homalin, like most of Myanmar, mining sectors may be formal or informal. The formal mining sector consists of companies that operate with permits issued by the ME2, which operates under Myanmar's Ministry of Natural Resources and Environmental Conservation. All other mining operations are considered informal.

2.2 | Questionnaire design

We designed a questionnaire to characterize the agricultural and gold mining sectors. Based on the evidence from previous studies which suggested that livelihood approaches fail when the proposed livelihood does not fully substitute the one it intends to replace or that migration in or out of the study area will undermine the goals of the livelihood intervention (Wright et al., 2016), and that enforcement approaches fail when they provide insufficient economic deterrence (Milner-Gulland & Leader-Williams, 1992), we designed a questionnaire to assess whether these interventions were likely to deter IGM. The categories were chosen based on our initial field visits and reports of the sector (Myanmar Centre for Responsible Business, 2018).

For comparative purposes, we collected data on miners in the formal sector, miners in the informal sector, and farmers who constituted the majority of residents in the study area. The main analytical focus was on understanding how interventions would affect the behavior of miners in the informal sector. Unless stated otherwise, all questionnaire items were open questions.

To understand the context of livelihood decisions, we collected basic demographic variables—age, gender, ethnicity, and education status. We asked respondents about past migrations and livelihood changes and conditions under which they would do so in the future. To assess the complementarity of mining and farming in terms of income, we asked respondents to estimate the percentage of their individual annual income earned from mining, agriculture, or other livelihoods. We also asked respondents why they did or did not practice mining and agriculture. We asked respondents what they perceived to be the positive and negative impacts of mining, and whether they thought mining should continue at the study site, as this will influence local support for policies.

The economics of current livelihoods shapes the policy space for enforcement and livelihood-based interventions. We asked mining respondents about their role in the operation, number of workers in both dry and wet seasons, salaries, costs, and quantities of key inputs (mercury, diesel, and engines), mine size, and the amount of gold extracted per day on average. We asked farming respondents about farm size, crop yields, and profits.

To assess current enforcement efforts, we asked informal mine bosses and workers about the frequency and effects of inspections. Since informal resource extraction activities are often informally regulated by local authorities (Duffy, 2005), we asked informal mining respondents if they paid any permission fees. We conducted additional key informant interviews about enforcement with township police and mining enterprise officials.

The questionnaire was prepared in English and translated to Burmese. Four Myanmar researchers, who all participated in the question formulation and translation, administered the survey in Burmese. The full questionnaire, in English and Burmese, is in the Appendix S1.

2.3 | Ethical approval

An Institutional Review Board approved the study design (NUS-IRB Reference Code S-17-243). We ensured free, prior, and informed consent among study participants. As informal gold mining operations are illegal under Myanmar law, we made the survey anonymous. We read a statement out to each potential participant informing them of the study purpose, its voluntary nature, potential risks of participation, and measures taken to minimize these risks. We did not record any names, addresses, company names, or GPS coordinates of respondents.

2.4 | Sampling

We administered the questionnaire to 226 respondents: 18 formal bosses (employers in the formal sector), 48 formal workers (employees in the formal sector), 31 informal bosses (employers in the informal sector), 59 informal workers (employees in the informal sector), 57 farmers (agriculturalists who may also participate in informal mining), and 13 subcontractors, employers who run independent mining operations within a subsection of a concession operated by a formal mining company.

For the formal sector, we randomly selected from a list of companies in the township from the head of the

miner's association. From selected companies, we randomly selected potential willing respondents from a list of employees. For other respondent categories, we asked a local facilitator to identify willing respondents in advance. We took this approach to ensure that we never had the identities of informal miners who did not want to participate in the research. Due to scarcity of available respondents in the informal mining sector, we interviewed all available respondents. For those cases, sampling was exhaustive rather than random.

2.5 | Analysis

We inductively coded qualitative responses to open questions (e.g., reasons for mining or not mining)—the codes emerged from the data. We carried out our data exploration, visualization, and analysis in R version 3.4.3 (R Core Team, 2017). We used the *tidyverse* package for data exploration and visualization (Wickham, 2017). As part of a post hoc analysis, we modeled the demographic predictors of openness to future migration—a key determinant of the scalability of proposed interventions—by fitting generalized linear mixed models with site as a random effect using the *lme4* R package (Bates, Mächler, Bolker, & Walker, 2015). We modeled the responses of the 152 respondents who gave a "yes" or "no" answer to the closed question of whether they were open to migrating in the future (eight respondents said they were unsure and 66 did not answer the question). The models contained up to four of five possible demographic predictor variables: migrant status ("residents" who had lived in the township for at least 15 years, and "migrants"), ethnicity (Shan, Bamar, or Other), age, gender, education code (0 = none, 1 = monastic education only, 2 = up to primary school, 3 = up to middle school, 4 = up to high school, and 5 = university). We did not include models with both ethnicity and migrant status as the two variables were highly correlated (all respondents from the Shan ethnic group were long-term residents). We therefore created 30 candidate models (Appendix S1), and ranked them by AICc using an information theoretical approach. We calculated pseudo-R2 using Nakagawa, Johnson, and Schielzeth's (2017) method, implemented using the *MuMIn package* (Barton, 2019). We checked model residuals for normality and homoscedasticity (see Appendix S1). We did this first for all respondents, and then repeated it for those working in the informal mining sector.

We conceived of two mechanisms by which law enforcement could make informal mining unprofitable, grounded in the actual operation of law enforcement in the study context. The first was to cause a temporary suspension of mining operations. The second, stronger level, is for the inspection team to confiscate the mining operation's engines. Under this scenario, the mining operation would have to replace their machinery after each inspection in addition to recouping the losses from paused operations. For this second scenario we considered two further permutations–one in which bosses still paid their workers, and one in which they did not. For each scenario, we calculated the daily profit by multiplying the reported daily gold extraction rates by the gold price ($43 USD/g) minus daily diesel consumption multiplied by the diesel price ($2.13 USD/g). We did not include mercury costs in these calculations because we did not obtain enough data on mercury use, and the limited data that we had suggested it was a relatively insignificant expense (median value: $0.41 per day).

Estimated daily profits = (daily gold extraction × gold price) − (daily diesel usage × diesel price).

We then calculated the amount of days (D_1) needed to operate in a month in order to recoup monthly fixed costs (Appendix S1).

D_1 = monthly wage bill/estimated daily profits.

For the second scenario (engine confiscation), we calculated the number of days (D_2) needed to break even as:

D_2 = (monthly wage bill + total engine cost)/estimated daily profits.

We calculated the frequency of inspection required to make inspection unprofitable by assuming that a mining operation would be unprofitable if the number of days available for mining per month is less than the number of days needed to break even (D_1 or D_2). We only received estimates from two respondents about the number of days that mining operations stop during inspection—6 or 10 days. We repeated the calculation with both of these estimates of the number of days during which mining cannot happen. Hence, if there are two inspections per month, 12 or 20 days, respectively would be unavailable for mining. For each informal mining operation, we calculated the frequency of inspection required to make it unprofitable as:

If equipment is never confiscated:

Inspections per month = $(30 - D_1)$/length of pause.

If equipment (engines) is always confiscated:

Inspections per month = $(30 - D_2)$/length of pause.

In both cases, length of pause was either 6 or 10 days.

These calculations did not include the cost of transporting engines or of replacing other mining-related equipment, and therefore our calculations underestimate the cost of replacing mining equipment and overestimated the frequency of inspection needed. The calculations also assumed that bosses would continue to pay wages during closure—while informal operations are not legally obliged to do so, we assumed that they would need to keep paying employees in order to maintain a viable workforce.

3 | RESULTS

Out of 226 respondents between November 2017 and January 2018, the majority (119) were migrants (born in a different township) and out of this total 106 had moved from different townships within the same region (Sagaing). The number of years that migrants had lived in the township ranged from 0 to 30, with a median of 5 years. The two main ethnic groups in our sample were Shan (89 respondents, all born in Homalin) and Burman/Bamar (126 respondents, 116 of whom were born in a different township). Our sample was mostly male (200 of 226 respondents).

Approximately half (29/57) of the respondents in the "farmer" category also practiced informal gold mining, and 64 of 169 respondents in the mining categories practiced agriculture. Informal workers were more likely to balance both agriculture and mining (31 of 49 respondents) than informal bosses (6 of 31 respondents). Respondents who practiced both agriculture and mining split work seasonally between mining and farming, in particular farming during the June–September monsoon season and mining from October to May. Many respondents had other additional livelihoods such as trade (Appendix S1).

3.1 | Overview of formal and informal mining sectors

Respondents identified two broad categories of gold mining in Homalin township, "water mining" (*yei-myaw*) and "land mining" (*kon-myaw*). "Water mining" operations (which 9 of 18 formal bosses and 21 of 30 informal bosses reported using) used suction dredges to transport water and soil from riverbeds, wetlands, or old tailings ponds through a pipe and onto a sluice. "Land mining" operations sprayed mine pits with high-pressure water hoses. The resultant slurry was pumped onto a wooden sluice. For both categories of mining, miners placed carpets onto the sluice. As the gold-bearing slurry ran down the sluice, gold particles were deposited onto the carpets. The miners removed the carpets and put them into water tanks, and extracted gold from the tanks by panning and amalgamating with mercury. Gold was then extracted from mercury by heating the Au-Hg amalgam until the mercury evaporates. The majority of informal mine bosses reported that the previous land use was an old mining site, whereas formal mine bosses were more likely to say that the previous land-use was forest or wetland (Appendix S1). While most informal sector bosses (20/28) reported operating their mines on sites previously used by the formal sector, only a

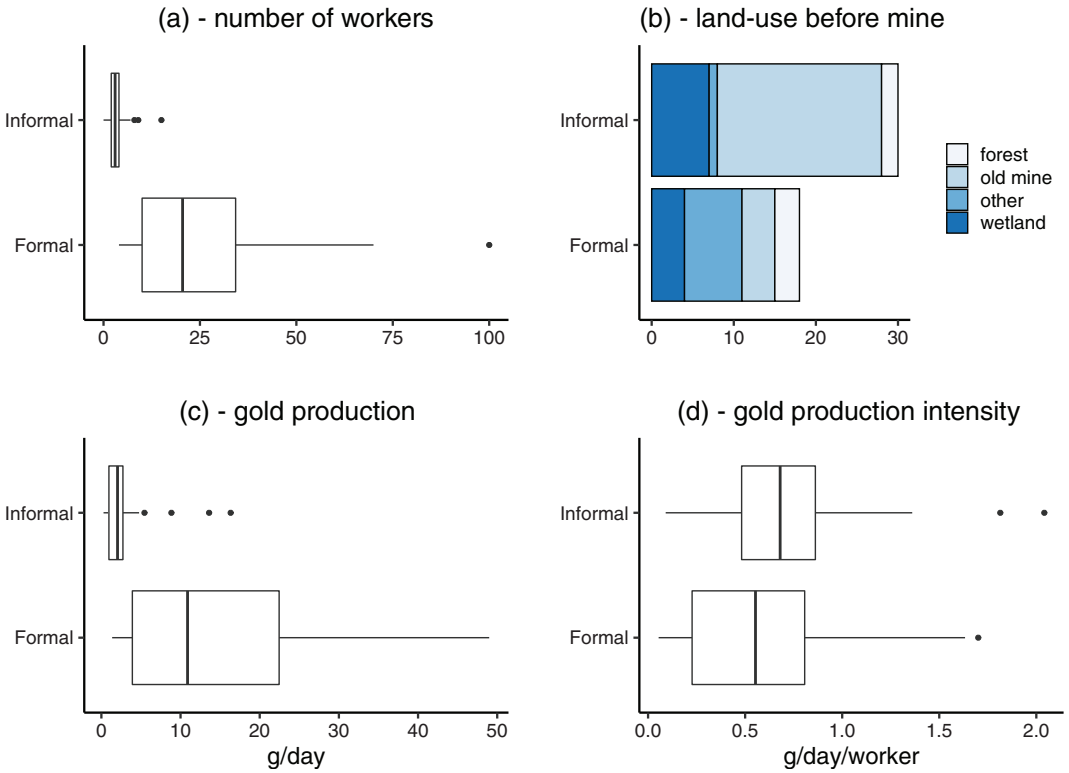

FIGURE 2 Comparison of formal and informal sector: (a) Number of workers in informal and formal mining operations in the open season (October–May); (b) Self-reported previous land-use before mine operation; (c) grams of gold produced per day; (d) gold produced per day per worker

minority of formal sector bosses (4/18) reported operating on previously mined sites (Figure 2b). Mine sizes on the formal sector are capped at 20 acres (8.09 ha) by Myanmar law, but we only received three responses about mine size from the informal sector (3, 5, and 20 acres) so we cannot draw any robust conclusions about average mine size.

3.2 | Overview of agricultural sector

Of the 115 respondents who practiced agriculture, 107 grew rice paddy as their primary crop (the other crops were coconut, cucumber, vegetables, and peanut). For rice farmers, the median farm size was 2.03 ha (IQR: 1.62–3.24), with median annual production of 4.2 t (IQR 2.52–8.4). The median household used all of this rice for household consumption (IQR 50–100%). Among the households that sold surplus rice, the median value of the rice sold was $462.40 (IQR: 272–816). The median wage for agricultural labor was $3.30 (IQR: 3.30–3.30) per day, or $102 per month.

3.3 | Mining sector operational practices, profits, and costs

Gold mining was highly profitable, in both the formal and informal sectors (Figure 2c,d). The median reported rate of gold extraction in the informal sector was 2.24 g/ha/day (interquartile range [IQR]: 1.67–2.46), which at the reported gold price of $43 USD/g equated to a median of $96 USD/ha/day (IQR: 71.64–105.95). After wages and diesel expenditure, informal mining operations had a median estimated net profit of $1,196.47/month (IQR: 500.54–2,202.95). Formal mines had similar rates of gold extraction per hectare (median: 1.34 g/ha/day, IQR: 0.48–3.15) but operated on a larger area—8.1 ha (20 acres) compared to informal mines (median: 1.22 ha, IQR: 0.71–4.66)—and generated higher estimated net profit per month (median: $5,658.86, IQR: $1,050.62–22,312.99).

Mining operations in the informal sector had a median of three employees (IQR: 2–4) in both "open" (drier period in October–May) and "closed" (monsoon period in June–September) seasons, while the median

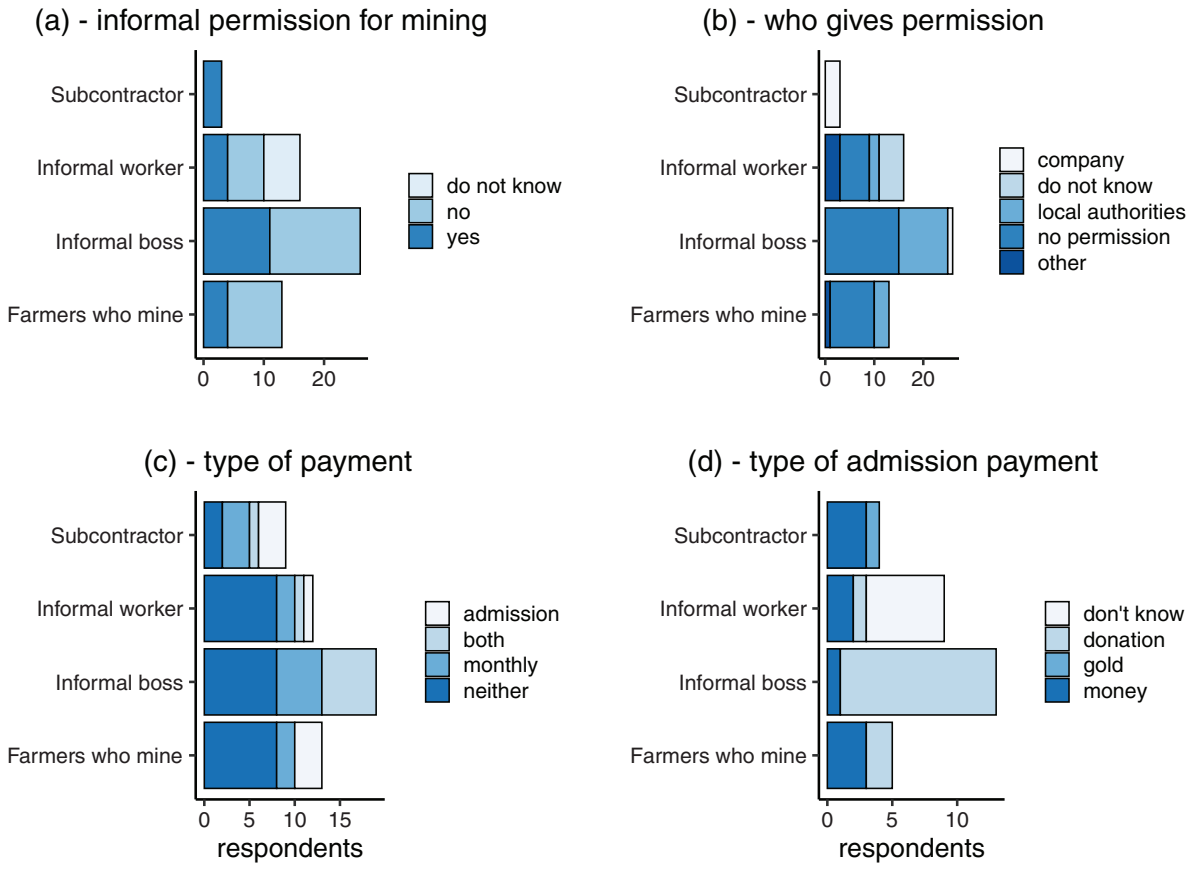

FIGURE 3 Informal sector permission structure: (a) whether respondents reported having permission from local authorities; (b) who (if anyone) granted permission; (c) what kind of payment they had to make (admission refers to an initial one-off fee); (d) what type of admission fee they paid, where relevant. Farmers are respondents who practiced both agriculture and mining

number of workers in the formal sector was 21 (IQR: 10–34) in the open season and 19 (7–28) in the closed season (which is the key period for planting and harvesting rice) (Figure 2a). Workers in both sectors were typically paid regular salaries in cash, but some workers reported being paid additional shares of gold produced. This latter practice was more frequent in the formal (11/48 formal worker respondents) than informal sector (4/59 informal worker respondents). Median salary in both the formal and informal sectors was $102 per month. Due to the larger scale of formal operations, formal operations had a wider range of roles, including cooks, accountants, and specialized equipment operators, while the informal sector was composed of bosses and general laborers.

3.4 | Mining sector regulation

While the formal sector was directly regulated by the national mining enterprise and department, the informal sector in our study sites had an unofficial parallel regulatory structure. Of 28 informal bosses who responded to a question regarding permitting, 19 reported a need to get permission from local authorities (typically the village head) to carry out mining and/or pay admission fees or donations (Figure 3). Admission fees were typically in the form of donations to village affairs, for example, schools and monasteries. In these cases, the informal mining sector operated under a parallel governance structure, paying fees, and taxes to local authorities and communities instead of formally to the government (Figure 3). However, in other cases the informal sector operated outside of any formal or informal permitting requirements. We do not have the full picture of the interactions between this informal permitting and the formal enforcement, but one respondent reported that in exchange for payment to the authorities they would be warned in advance of official inspections. As one informal mining respondent noted (we have changed Myanmar kyat to US dollars in the quote):

"*The police come and ask us to pay money.* [An informal] *mine owner has to pay $146. We have to pay village head about $22–29 per month. It is a kind of permission fee. The village head warns us when the police come. We also have to pay money when the military comes. We also have to transport them* [the military] *by boat. A mine owner has to pay about 26–33* [to the military]."

3.5 | Enforcement

We estimated that the median number of days required for an informal mining operation to pay off its monthly fixed costs was 6 days (IQR: 5–9 days). Put differently, inspectors would need to shut down operations for at least 25 days a month to make half of the informal mining operations unprofitable. The median mining operation would need to operate for 24 days a month (IQR: 16–56 days) to break even if engines were confiscated

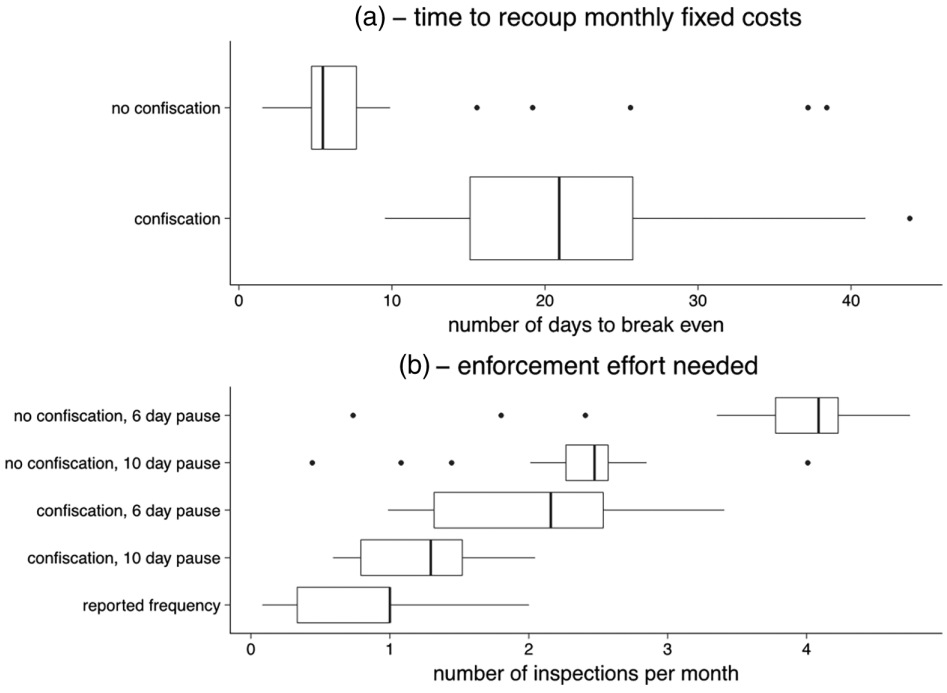

FIGURE 4 (a) Number of days required by an informal mining operation to recoup monthly costs under two scenarios—"confiscation" in which they need to repurchase their engines every month (under an inspection scenario in which equipment is confiscated every month)—and "no confiscation" in which their only fixed costs are salaries; (b) current reported frequency of inspection vs the inspection required to make mining unprofitable under different scenarios (work has to be paused for 6 or 10 days, and engines are or are not confiscated following inspections)

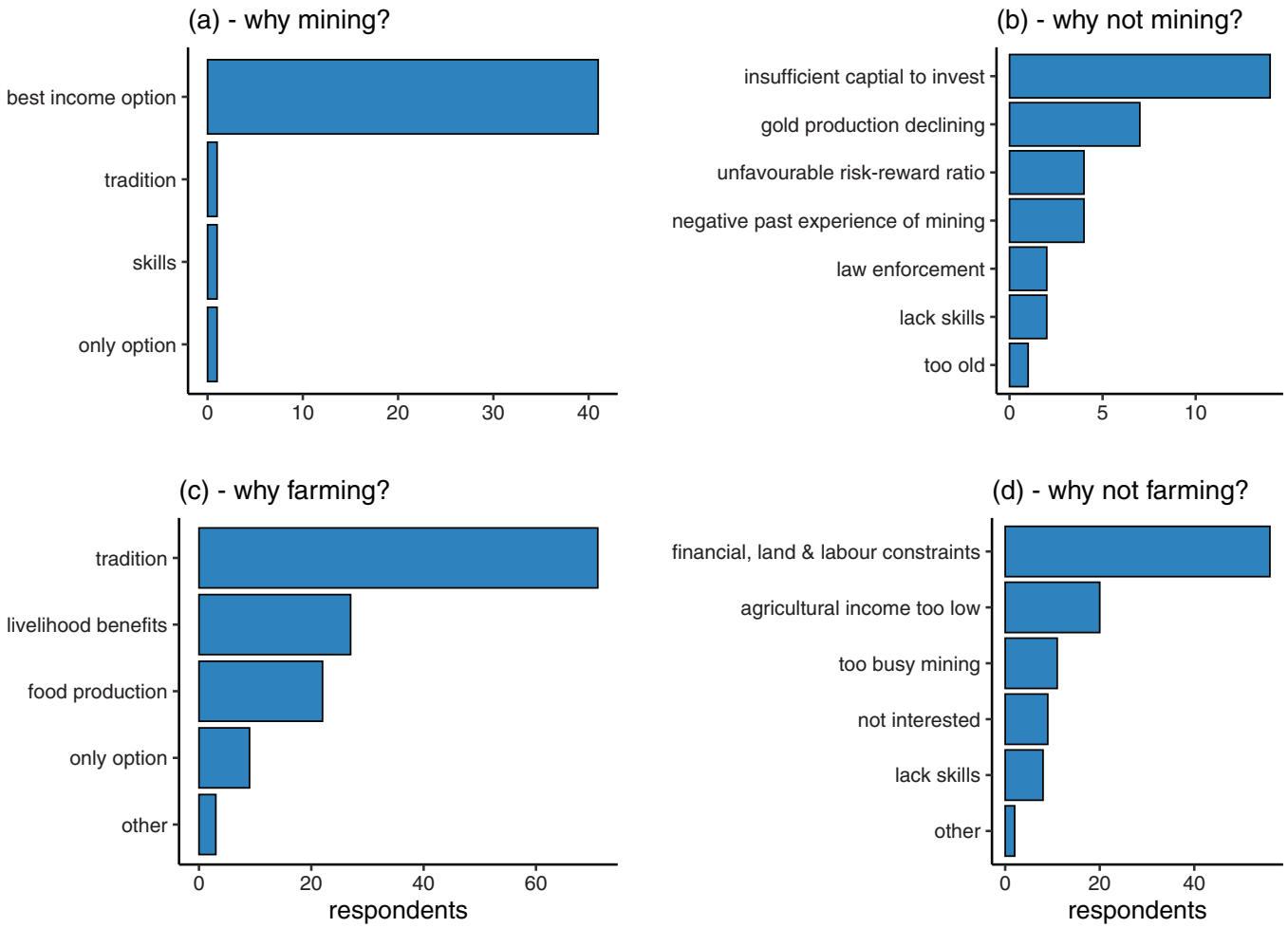

FIGURE 5 Reported reasons for participating, or not participating, in the mining and agricultural sectors, as coded and categorized by the authors (see Appendix S1 for full quotes and codes). The count represents the number of items a category was mentioned

(Figure 4a). According to this calculation, if informal mining operations had to replace their engines every month, and lost at least 7–8 days of work in the process, the mining would be unprofitable for the majority of informal mining operations (Figure 4b). This contrasts unfavorably to the actual reported frequency of inspections in the informal sector, which was a median of 0.17 per month (IQR 0–1). Informal mining respondents reported that the main effect of the inspections (if any) was that operations were temporarily paused. Only one respondent reported equipment confiscation, and none reported arrests. Pauses impose costs, as informal bosses must still pay workers. Given the disparity between the reported level of enforcement and that needed to deter informal mining, a substantial increase in enforcement effort and funding would therefore be needed to effectively deter informal gold mining. Police and Mining Enterprise key informants reported that at the time of the interviews there was no official budget for enforcement and that it was therefore subsidized by per diems paid by the formal sector to the township Mining Enterprise.

3.6 | Livelihood decision-making

Mining was perceived as the best income source, while farming had subsistence and cultural value. Key reasons for mining were the superior earning potential of mining, especially compared to agriculture (Figure 5a). Key reasons for not mining were financial constraints: lack of investment money and hired labor, rather than lack of interest or negative attitudes toward mining (Figure 5b). In contrast, tradition was the main motivation for farming. Some respondents also viewed it as a more sustainable long-term livelihood than mining (Figure 5c). The main reasons for not farming were lack of farmland and low potential income (Figure 5d).

3.7 | Perceptions of the mining sector

Mining was valued for enabling local development, particularly for schools (85 respondents), adorning religious buildings with gold (74 respondents), and infrastructure

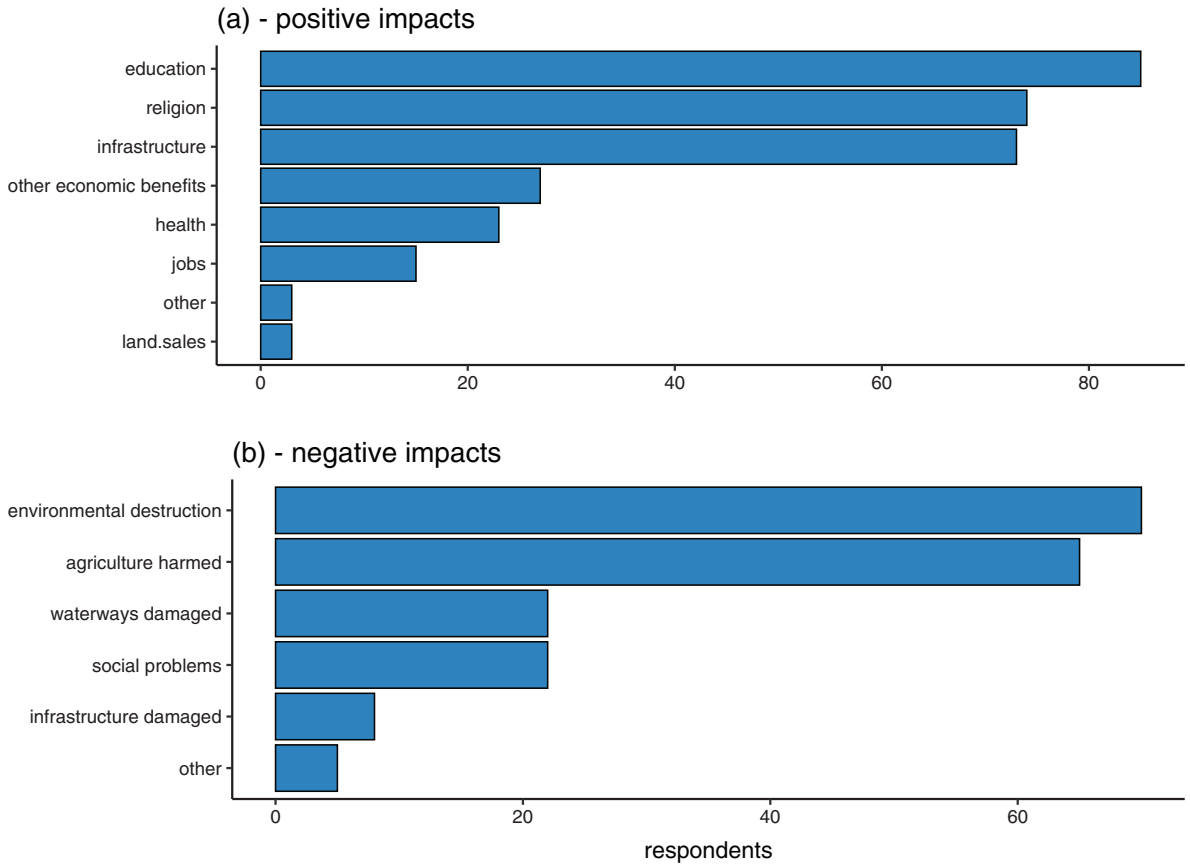

FIGURE 6 Perceptions of positive and negative impacts of mining

(73 respondents). Perceived negative effects of mining included environmental damage (70 respondents), decreased agricultural productivity (65 respondents), and social problems such as increased crime rates and drug abuse (22 respondents) (Figure 6).

3.8 | Drivers of willingness to migrate

Most migrants listed economic push and pull factors as the key reason for having migrated. Among informal miners, male (coefficient 2.02, *SE* 1.45), older (coefficient 0.08, *SE* 0.05), and more educated (coefficient 1.21, *SE* 0.64) respondents, and those with recent history of migration (coefficient −3.21, *SE* 0.78) were more likely to consider migrating in the future (full model, #15 in Table 1, Appendix S1). The best model of openness to future migration (#5 in Table 1) contained just migrant status (coefficient −3.03, *SE* 0.70) and education (coefficient 0.53, *SE* 0.43) as fixed effects, but many models had similar AICc scores (δ AICc <10; Table 1). The estimated R2 for this model was 0.35 (delta) or 0.45 (theoretical), cf R2 = 0.01 for the null model and R2 = 0.50 or 0.56 (delta and theoretical respectively) for the full model. Past history of migration was a strong predictor of future willingness to migrate. Most migrants were willing to migrate in the future, while most long-term residents were unwilling to ever move (Table 1). The modeled

TABLE 1 Best models for willingness to migrate in the future

Factors	AICc	δAICc	R2 (δ)
Migrant status + education level	62.49	0.00	0.39
Migrant status + education level + age	62.63	0.14	0.44
Migrant status + education level + age + gender	62.86	0.37	0.50
Migrant status + education level + gender	63.82	1.33	0.41
Migrant status	68.18	5.69	0.34
Migrant status + gender	68.92	6.43	0.38
Null model	95.41	32.93	0.01

Note: Migrant status is a binary variable ("resident" for respondents who have lived in the township for at least 15 years, and "migrant" for those who arrived more recently), education level is a categorical variable describing the highest level of education (e.g., "primary," "middle," "secondary"), and ethnicity is a categorical variable with three levels ("Shan," "Bamar," or "Other"). AIC values and conditional R2 values (delta) calculated using the lme4 and MuMIn packages in R, respectively.

probability of a respondent educated to middle school level (average values for these factors) to be willing to migrate was 0.12 for long-term residents and 0.74 for migrants (Appendix S1). Respondents reported three general economic scenarios under which they would migrate—(a) after meeting a set financial target, (b) better livelihood opportunities elsewhere, or (c) mining in Homalin being no longer viable.

4 | DISCUSSION

Current Myanmar government policy focuses on trying to restrict the informal gold mining sector through enforcement and providing alternative agricultural livelihoods to long-term residents. These policies framed our research, and we found that neither enforcement nor alternative livelihoods, as currently practiced, are likely to deter informal gold mining.

4.1 | Enforcement is unlikely to deter informal gold mining

The informal gold mining sector was highly profitable and in some cases tacitly condoned by local authorities, as suggested by permission fees that respondents reported paying (Figure 3). This parallel governance structure has been reported in other informal mining systems in Madagascar and Indonesia (Duffy, 2005; Peluso, 2018). Even without interference between informal payments and official inspections, our calculations suggest that inspections—causing operations to be paused for 6–10 days—would need to be applied at unrealistically high frequencies given budgetary and staff constraints for law enforcement officials in order to be successful (Figure 4).

Inspections imposed economic costs on the informal sector, due to lost workdays, but enforcement was too infrequent to act as a deterrent (Figure 4) and likely to be undermined by corruption (Figure 3). Our calculations suggest that sufficiently costly enforcement measures—for example confiscating equipment or visiting more frequently to prolong pauses—could make IGM unprofitable (Figure 4). This could in principle work, if there were sufficient funding for law enforcement officials to confiscate and destroy mining equipment with sufficient regularity to make mining unprofitable. Since the median mining operation can recoup its monthly wage bill after just 6 days of operation, the current enforcement context, in which work is paused for a few days every month or once in every 2 months, cannot economically deter mining. Instead, our calculations suggest law enforcement agencies would need to confiscate or destroy the engines of informal mining operations once a month to put most informal mining operations out of business. This estimate could be improved by modeling adaptive responses by informal miners to high enforcement and/or by incorporating a realistic threat of imprisonment.

The estimated level of enforcement needed to make mining unprofitable contrasts unfavorably to the situation on the ground. There is no official budget for law enforcement and all revenue is provided by official fees paid to inspectors by formal companies. Even if the budgetary issues could be addressed, corruption is highly prevalent in Myanmar (Transparency International, 2017). We therefore conclude that under the likely local budgetary and governance context, law enforcement is not currently a viable deterrent to the informal gold mining sector.

We focused on frequency of inspections and did not consider arrests due to current enforcement practices which rarely if ever lead to arrests. A concerted military-led crackdown on illegal mining could in theory drive out illegal mining operations, as has occurred recently in Tanai Township in Kachin State ("Lawmaker Criticizes Military Action in Illegal Mining Areas, 2017"), although military operations in areas of natural resource extraction have been motivated by seizing control over natural resource rents rather than environmental protection (Woods, 2011). It is possible that more frequent arrests and imprisonment would provide a stronger deterrent. However, this could risk human rights abuses and unfair application of penalties toward the most marginalized miners, so we would urge caution in promoting this suggestion. Indeed, military-led crackdowns on illegal gold mining in Ghana have been criticized for human rights abuses and for failing to tackle the root drivers of IGM (Hilson, 2017).

Our study is the first to estimate the level of enforcement required to make informal gold mining unprofitable. Further research could be informed by the literature on deterring poaching. Models of anti-poaching enforcement in Zambia revealed that increased probability of detection was more likely to be an effective deterrent than increased fine or prison terms (Milner-Gulland & Leader-Williams, 1992). Further models could test this, but given the similar context, we expect this may also apply to gold mining in Myanmar. A further complication of enforcement is corruption. Successful cases of corruption reduction in 19th century Britain and 21st century Georgia suggest that is possible, but usually when elites with decision-making powers have no vested interest in corruption (Popa, 2015; World Bank, 2016). Given the profitability of gold mining, and the observed willingness of authorities to extract fees from the

informal sector, the prospects of such reforms in this situation remain limited. Further empirical and modeling work in corruption reduction remains a key research frontier given its relevance to many conservation issues (Smith, Biggs, St John, 't Sas-Rolfes, & Barrington, 2015).

4.2 | Agriculture-based livelihoods are unlikely to succeed

Agriculture and mining were complementary livelihoods—meeting different needs and operating in different seasons—suggesting that any livelihood-based intervention around agriculture or plantations (as currently proposed by the regional government) is unlikely to prevent mining. Furthermore, non-mining participants cited lack of money to invest into mining as a major constraint on mining (Figure 5). An unintended consequence of providing additional livelihood opportunities is that it might provide more opportunities to invest in mining; something which will need to be anticipated if local economic prosperity improves. This has parallels with AL programs to provide alternatives to poaching, which have sometimes backfired by enabling poachers to buy better equipment. In the heterogeneous community we studied, migrant status (correlated with ethnicity) had a strong effect on stated willingness to migrate in the future—the long-time resident (mostly Shan) community is culturally tied to the land and unwilling to migrate, whereas the migrant (mostly Bamar) respondents were willing to migrate in response to economic incentives (Table 1, Appendix S1).

Informal mining respondents in our sample were aware of the negative environmental and social consequences of mining, but pursued it because it was the most viable income source (Figure 5). Our work builds on an emerging consensus that informal miners make economically rational decisions given their limited livelihood opportunities, as demonstrated in Suriname and Ghana (Heemskerk, 2002; Hilson & Potter, 2004). Many respondents practiced agriculture and mining as complementary livelihoods, with agriculture for food and mining for income, as in artisanal mining systems across sub-Saharan Africa (Hilson, 2016). This suggests that plantation/agriculture based alternative livelihood interventions are unlikely to fully substitute mining, a common problem in AL projects (Wright et al., 2016), for example, cacao plantations did not substitute poaching because it provided money at different times of the year (van Vliet, 2010).

Livelihood and enforcement interventions are further complicated by the heterogeneity of the community. Many miners (approximately half in our sample) were migrants from other townships, and migration history was a strong predictor of willingness to migrate in the future (Figure 2, Table 1, Appendix S1). Livelihood-based interventions would likely target the long-term residents, leaving migrant miners to either continue mining or migrate and potentially mine elsewhere. Even if every miner in Homalin township stopped mining, there would be a strong incentive for people in other parts of Myanmar to migrate to the mining sites. A further challenge is that if the alternative livelihood is intended to be a physical replacement of the mining activity—for example, bamboo plantations on old mining sites—then the alternative livelihood would also have to immediately offset the opportunity costs of not mining. We therefore conclude that the assumptions underpinning a successful livelihoodbased intervention—full substitution, community homogeneity, and scale-ability (Wright et al., 2016) are not met, and that livelihood-based interventions are unlikely to succeed.

4.3 | Where should Myanmar mining policy focus?

Our finding that both formal and informal workers split their time between mining and farming but that mining bosses in both sectors specialize in mining suggests that alternative livelihood schemes targeting informal bosses (both migrant and resident) specifically might be more effective. Moreover, our finding that the informal sector largely operates on mine sites abandoned by the formal sector suggests that efforts to control the environmental effects of gold mining should instead focus on controlling the expansion of the formal sector. Efforts to control the damage caused by the informal sector could be more effective if enforcement effort were concentrated on preventing mine expansion to new areas, instead of preventing informal mining on already mined lands. Allowing informal mining on already mined lands would also make it easier to work with the informal mining communities to introduce technologies that eliminate mercury emissions, such as the use of mining retorts (Veiga, Angeloci-Santos, & Meech, 2014).

After completion of our fieldwork, Myanmar released new mining rules in February 2018 which enable regional governments to grant artisanal (1 acre) or small scale (4 acre) gold mining licenses. Formalization of the artisanal sector was recommended in a review of the mining sector (Myanmar Centre for Responsible Business, 2018) and has the potential to enable miners to pursue their principal livelihood within regulations to minimize the worst impacts of mining. Formalization programs elsewhere have succeeded when bureaucratic and financial barriers to registration were low, as in Guyana (Hilson & Maconachie, 2017). However, the

currently proposed cost of permits for small-scale mines in Sagaing is $US 7,895 which is likely to provide a significant barrier. Based on our fieldwork and the experience of formalization projects elsewhere, we recommend reducing the permit fees for small-scale mining and artisanal mining to make them accessible to informal miners, and only issuing them on previously mined sites to reduce the environmental impact of the sector.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

All authors meet the author contribution criteria. G.W.P. and E.L.W. conceived of the study and led its design. A.C.M., L.R.C., A.D., M.R., and D.S.V. contributed to study design. A.C.M., Z.M.A., A.K.K., and Y.M.S. conducted the questionnaires, while JDTDA collected the remote sensing data. A.C.M. translated the questionnaires from English to Burmese and translated the responses back to English. A.C.M. coded the responses with G.W.P. G.W.P. led the analyses and writing with advice from all coauthors, especially E.L.W. All authors contributed to revision and preparation of the final manuscript.

DATA AVAILABILITY STATEMENT

To protect the anonymity of study participants under the terms of our ethics approval (NUS-IRB Reference Code S-17-24) we cannot share the raw data.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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